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**LABORATORY SIMULATION OF
SOLAR WIND - EARTH INTERACTION**

by Donald L. Chubb

Lewis Research Center

Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

A laboratory simulation experiment of the interaction of the solar wind and the earth's magnetic field is being conducted at Lewis Research Center of NASA. The plasma flow is produced by an MPD arc and a magnetic dipole is used to simulate the earth's magnetic field. The initial investigations of the stagnation region of the flow show a rapid rise in the plasma potential. The magnetic field in this region is also altered from the dipole type behavior it exhibits when no flow exists. This region of change in plasma potential and magnetic field has a thickness characterized by the electron cyclotron radius. It appears to be a merging together of a collisionless deceleration and stagnation of the flow. However, whether or not a collisionless shock wave exists has not been conclusively demonstrated.

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SUMMARY

A laboratory simulation experiment of the interaction of the solar wind and the earth's magnetic field is being conducted at Lewis Research Center of NASA. The plasma flow is produced by an MPD arc and a magnetic dipole is used to simulate the earth's magnetic field. The initial investigations of the stagnation region of the flow show a rapid rise in the plasma potential. The magnetic field in this region is also altered from the dipole type behavior it exhibits when no flow exists. This region of change in plasma potential and magnetic field has a thickness characterized by the electron cyclotron radius. It appears to be a merging together of a collisionless deceleration and stagnation of the flow. However, whether or not a collisionless shock wave exists has not been conclusively demonstrated.

INTRODUCTION

For the past few years NASA LeRC has been conducting preliminary experiments on the laboratory simulation of the interaction of the solar wind with the earth's magnetic field (ref. 1). Recently a detailed plasma diagnostics study of these experiments has been initiated. This report will report on the results of this diagnostics program.

The electric thruster vacuum facilities available at Lewis are ideal for such an experiment. A large 15-foot diameter by 65-foot long vacuum tank houses the experiment. The pumping speed of this tank is 500 cubic meters per second in the 10^{-6} - to 10^{-5} -torr pressure range.

To simulate the solar wind a magnetoplasdynamic (MPD) arc was used. Hydrogen is the propellant gas. This device is being studied as a possible thruster for deep space missions (ref. 2). A magnetic dipole is used to simulate the earth's magnetic

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field. The axis of the dipole is aligned perpendicular to the plasma flow.

Initial investigations have been confined to the stagnation region of the flow where a collisionless shock wave, similar to the earth's bow shock wave, should exist. The structure of this region was determined by measuring the plasma potential and magnetic field profiles. Currently, the electron number density and temperature profiles are also being investigated.

DIAGNOSTICS

Figure 1 shows a side view of the experimental apparatus. The magnetic dipole is

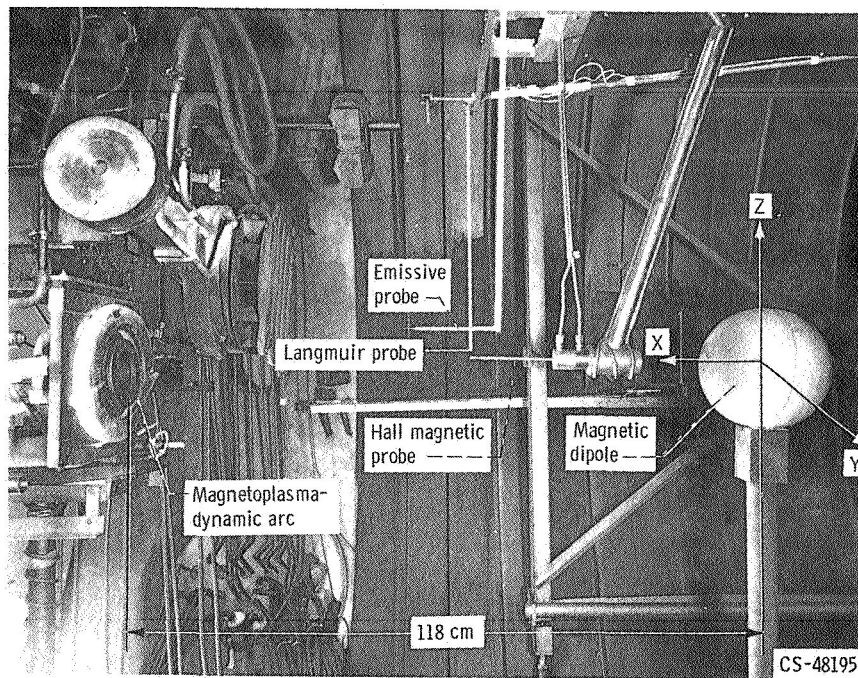


Figure 1. - Diagnostic equipment for solar wind simulation experiment.

enclosed in an insulating spherical shell. Shown are the three probes that are being used to determine the plasma properties. They are mounted on a traversing rake that is movable in the axial, transverse, and vertical directions. The emissive probe is used to measure the plasma potential. The Hall magnetic probe is water cooled and is aligned to measure the magnetic field in the z-direction. A 0.001-inch-diameter tungsten wire Langmuir probe is being used to determine the electron density and temperature. The thrust and hydrogen flow rate were measured as described in reference 2.

EXPERIMENTAL CONDITIONS

The values of the significant plasma properties that exist in the plasma flow are given in table I for both the experiment and the solar wind. To produce a collisionless plasma flow such as exists in the solar wind the characteristic collision mean free paths must be large compared to the dimensions of the experiment. Other conditions that must be satisfied to simulate the entire earth solar wind interaction are discussed in reference 1. In this experiment the distance between the MPD arc and the dipole (fig. 1) is slightly over 1 meter and the diameter of the beam is about 1 meter. The values of the electron-ion and electron-neutral mean free paths (table I) are an order of magnitude

TABLE I. - PROPERTIES OF PLASMA FLOW

| Plasma property | Solar wind experiment | Solar wind |
|---|--------------------------|--------------------|
| Flow velocity, u_1 , m/sec | 5×10^4 | 5×10^5 |
| Electron number density, n_1 , cm^{-3} | 2.6×10^{10} | 3 |
| Electron temperature, kT_{e1}/q , V | 7 | 7 |
| Upstream magnetic field, B_1 , T | 3.5×10^{-4} | 4×10^{-9} |
| Upstream sonic Mach number, M_s | 1.5 | 15.0 |
| Ratio of kinetic pressure to magnetic pressure, $\beta = (n_1 k T_{e1}) / (B_1^2 / 2\mu)$ | 0.8 | 0.6 |
| Electron-Ion mean free path, m | 10 | 10^5 |
| Electron-Neutral mean free path, m | 10 | ----- |
| Ion-Neutral mean free path, m | 1 | ----- |
| Debye length, m | 10^{-5} | 10 |

greater than the dimensions of the experiment. However, the ion-neutral mean free path is about the same size as the dimensions of the experiment. This is one of the reasons this investigation has been confined to the region close to the MPD arc where the hydrogen ions are less likely to collide with a background gas atom. Within this first 1/2 meter of the arc lies the region where the plasma flow is being decelerated and compressed by impingement on the dipole magnetic field. If the flow velocity is high enough a collisionless shock will occur in this region. The mean exhaust velocity of the MPD arc, u_1 , was determined from the measured thrust and mass flow.

It is important to note that for this experiment the ratio of the kinetic pressure to the magnetic pressure, $\beta = 0.8$, is close to that for the earth's bow shock, which is about 0.6. In the experiment of Pugh and Patrick (ref. 3) β has a much lower value of 0.2.

RESULTS AND DISCUSSION

Figure 2 shows the experiment in operation. The view is at an angle of approximately 45° from slightly behind the MPD arc. All the initial measurements have been made on the center line of the flow in the bright region just downstream of the MPD arc.

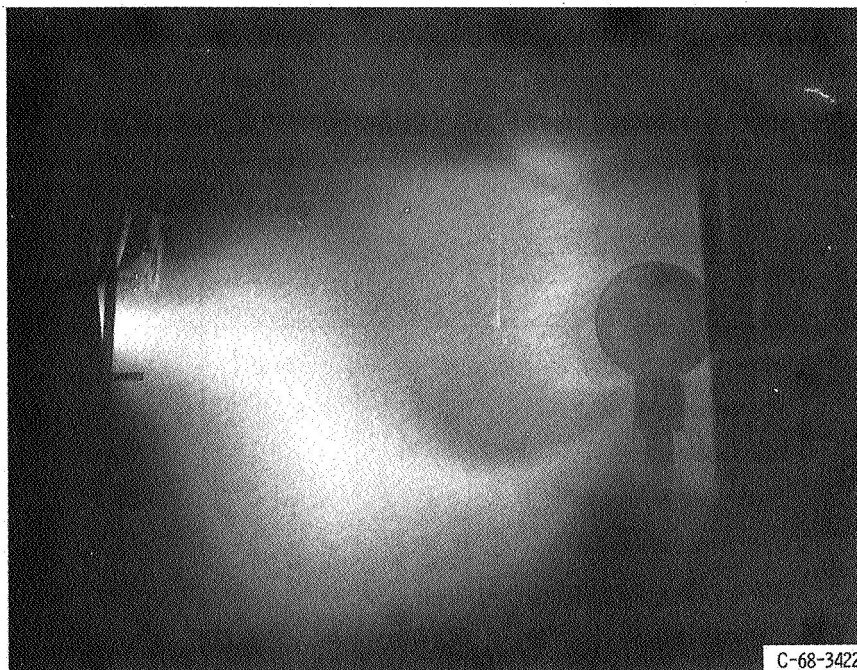


Figure 2. - Solar wind simulation experiment.

The plasma potential, V_p , relative to the tank-wall obtained with the emissive probe is shown in figure 3 as a function of distance from the dipole, x . In figure 4 the magnetic field perpendicular to the flow is presented as a function of x . The output of the emissive probe and the Hall magnetic probe were read on the y-axis of an x-y plotter and the position of the probe on the x-axis. As a result a continuous plot of V_p and B_z as a function of x is obtained. Two different profiles of V_p are shown in figure 3. The only major difference between the two is that the region of rapid increase moves back about 4 centimeters for the case where the dipole current is 495 amperes. This is as expected, since the stagnation magnetic field will be closer to the dipole for the lower current.

Both potential profiles show a rise of about 12 volts in the initial discontinuity. This rising potential region may be a normal shock with the potential increase corresponding

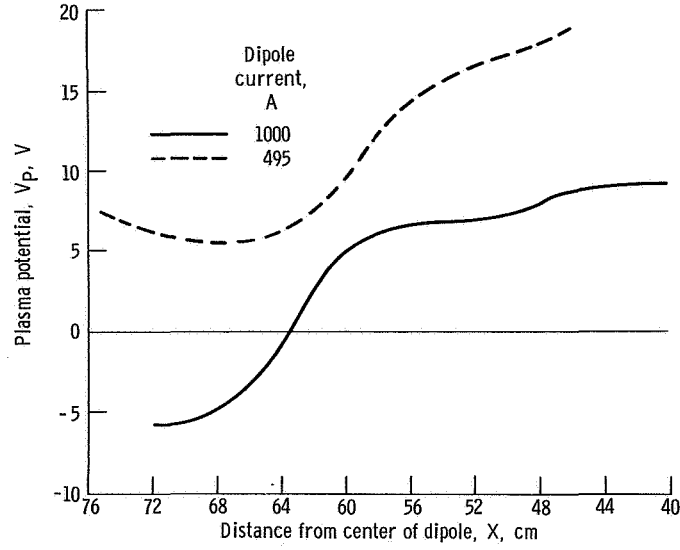


Figure 3. - Plasma potential profile.

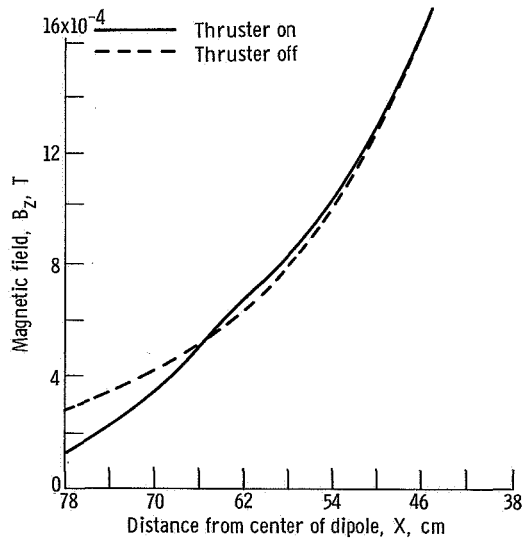


Figure 4. - Magnetic field perpendicular to plasma flow.
Dipole current 1000 amperes.

to the velocity decrease associated with the shock. If this is so then

$$\frac{1}{2} m_o (u_1^2 - u_2^2) = q \Delta V_p \quad (1)$$

where u_1 is the upstream velocity, u_2 is the downstream velocity, m_o the ion mass, q the charge, and ΔV_p the change in potential. If $\Delta V_p = 12V$, $u_1 = 5 \times 10^4$ meters per second, then for hydrogen ions, equation (1) yields the following for u_2 .

$$u_2 = 4.5 \times 10^3 \text{ m/sec}$$

and

$$\frac{u_1}{u_2} = 11$$

The limiting velocity ratio for a normal MHD shock (ref. 4) is 4. Therefore, this potential jump cannot represent a shock. However, it may represent the total velocity change that will occur across a shock and stagnation region together. The potential change required to stagnate hydrogen ions moving with a velocity of 5×10^4 meters per second is 13.1 volts.

To assure the existence of a shock the upstream Mach number, M_1 , must be greater than one, where M_1 is defined as follows:

$$M_1 = \frac{u_1}{\left(a_1^2 + v_{a1}^2\right)^{1/2}} \quad (2)$$

where

$$a_1 = \sqrt{\frac{5kT_1}{3m_o}} \quad (3a)$$

is the upstream sonic speed and

$$v_a = \frac{B_1}{\sqrt{\mu m_o n_1}} \quad (3b)$$

is the upstream Alfven speed.

If a Mach number is calculated using the measured values of a_1 , T_1 , n_1 , and B_1 given in table I, then we find $M_1 \sim 0.9$. However, if $B_1 = 2$ gauss, which, according to figure 4, occurs slightly upstream of the discontinuity, then $M_1 \sim 1.2$. From these results it is not clear that $M_1 > 1$ at the discontinuity. It may be that the flow is being compressed without the formation of a shock.

The thickness of the potential jump region is about 10 centimeters. The upstream electron cyclotron radius,

$$r_{e1} = \frac{\frac{v_{e1}}{\omega_{e1}}}{\frac{qB_1}{m_e}} = \frac{\sqrt{\frac{8kT_1}{\pi m_e}}}{\frac{qB_1}{m_e}} \sim 3.5 \text{ cm} \quad (4)$$

while the ion cyclotron radius,

$$r_{i1} = \frac{u_1}{\omega_{i1}} = \frac{u_1}{\frac{qB_1}{m_i}} \sim 200 \text{ cm} \quad (5)$$

The so-called Chapman-Ferraro-Rosenbluth collisionless sheath thickness (ref. 5), which is proportional to the ratio of the speed of light to the electron plasma frequency is the following.

$$\delta_{CFR} = \frac{c}{\sqrt{2} \Omega_{e1}} = \frac{c}{\sqrt{\frac{2q^2 n_1}{\epsilon_0 m_e}}} \sim 1.5 \text{ cm} \quad (6)$$

This quantity is the characteristic length for a beam plasma to be stagnated by a magnetic field. Referring to equations (4) to (6), it appears that the electron cyclotron radius is the dimension that characterizes the thickness of this potential jump. This result agrees with the model Tidman (ref. 6) presents for the earth's bow shock.

Pugh and Patrick (ref. 3) find that the characteristic dimension of their shock front is the ion cyclotron radius defined as follows.

$$r_{pp} = \frac{u_i}{\omega_{i1}} \quad (7a)$$

where,

$$u_i = V_A = \frac{B_1}{\sqrt{\mu m_0 n_1}}$$

is the Alfven speed. Equation (7a) therefore becomes

$$r_{pp} = \frac{c}{\Omega_{i1}} = \sqrt{\frac{2m_o}{m_e}} \delta_{CFR} \sim 87 \text{ cm} \quad (7b)$$

where Ω_{i1} is the upstream ion plasma frequency. For this experiment r_{pp} is much larger than the thickness of the discontinuity.

Another interesting comparison with the Patrick and Pugh experiment (ref. 7) is that they find no potential jump through their shock front. Rather they find that the relation,

$$\vec{E} + \vec{u} \times \vec{B} = 0 \quad (8)$$

is satisfied. So the streamlines of the flow represent equal potential lines. Also, from equation (8),

$$u = \frac{E_y}{B_z} \quad (9)$$

The electric field, E_y , was measured with the emissive probe and found to be $E_y \sim 0.3$ volts per centimeter. Therefore for $B_1 \sim 3$ gauss,

$$u \sim 10^5 \text{ m/sec}$$

which is a factor of 2 larger than the measured value of u_1 . It therefore appears that equation (8) does not apply to this experiment.

Figure 4 shows that when the thruster is not operating the magnetic field has the usual $1/x^3$ dependence of a dipole field. With the thruster operating the magnetic field shows a change occurring in the same location as the rapid rise in the plasma potential. If we consider the region of change as lying between $x \sim 69$ centimeters and $x \sim 59$ centimeters then,

$$\frac{B_2}{B_1} \sim \frac{8.0}{3.5} = 2.3$$

If the change in magnetic field is assumed to occur across a normal MHD shock, then from shock relations (ref. 4), this corresponds to $M_1 \sim 2.2$. This Mach number is

higher than expected. Thus the magnitude of the magnetic field change also supports the contention that this region of charge is not just a shock.

Besides the fact that it is not known for certain that $M_1 > 1$, the other significant point that arises in the experiment is that there does not appear to be a separation between the shock front and the stagnation region. This point has already been discussed in connection with the plasma potential and magnetic field profiles. The shock, if there is one, is probably merged into the stagnation region. The rise in potential at $x = 48$ in the plasma potential profile (fig. 3) is probably behind the stagnation point since it occurs in the dark region of the flow (fig. 2). The magnetic field profile (fig. 4) shows no second "bump" that might indicate a stagnation point. Based on supersonic flow theory, the lack of separation between the shock and stagnation point is not surprising. For a sphere with $M_s = 1.5$, the detachment distance for the bow shock is about 1/2 the radius of the sphere (ref. 8). In this experiment the equivalent sphere radius is about 60 centimeters. Therefore, the detachment distance, based on supersonic flow theory, should be about 30 centimeters. The region of rapid change has a thickness of 10 centimeters. Therefore, the condition that the detachment distance be much larger than the shock thickness in order to insure separation between the shock and stagnation point is not satisfied.

Some idea of the magnitude of the stagnation point magnetic field can be obtained by equating the stagnation point magnetic pressure to the free stream momentum flux plus pressure.

$$\frac{B_s^2}{2\mu} = m_o n_1 u_1^2 + n_1 k T_1 + \frac{B_1^2}{2\mu} \quad (10)$$

Using the values given in table I,

$$B_s \sim 7 \text{ gauss}$$

Referring to figure 4 we see that the 7-gauss point occurs at the end of the discontinuity. Based on this result it appears that the stagnation region occurs within the region where the magnetic field deviates from the dipole field.

CONCLUSION

A region of rapid change in the plasma potential and magnetic field of a hydrogen plasma impinging on a magnetic dipole has been measured. The thickness of this region (10 cm) is characterized by the electron cyclotron radius. It appears that this region

may be the merging together of a collisionless shock and the stagnation region of the flow. Whether or not a shock exists, however, has not been conclusively demonstrated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 10, 1968,
129-02-08-03-22.

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